Echo Planar Imaging (EPI) Ghost Removal

Advantage statement: EPI (Echo Planar Imaging) is an important imaging experiment wherein images can be obtained in about 50-100ms. EPI is the experiment of choice for Functional MRI (fMRI) of the brain. The regions shown in Figure 1 (top row) represent small signal level changes in the rat brain caused by stimulating the front and hind paws. However, it is also a very demanding experiment because it requires very large (readout) gradients to be switched rapidly and is prone to image artifacts caused by non-ideal behavior of the gradients and B_0 inhomogeneity. The latter can cause large signal and image distortions and is corrected by proper shimming. Varian has developed a new method for EPI ghost removal, implemented on the new Varian MRI System, which delivers superior performance in reducing ghost artifacts over the conventional methodology.

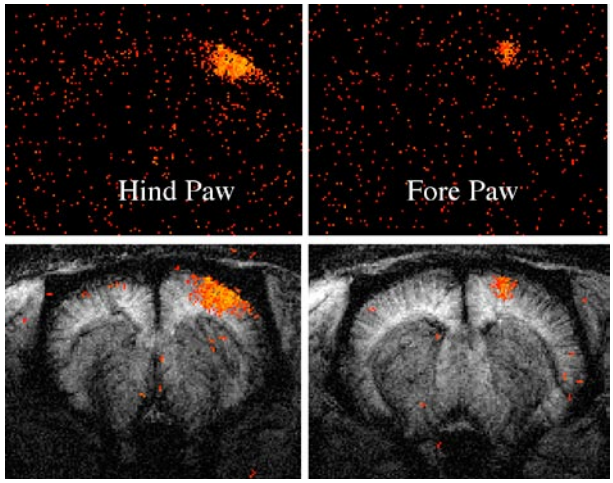

Figure 1 Functional MRI using Echo Planar Imaging

EPI Ghosts

One of the notorious artifacts in EPI is the Nyquist or half-FOV ghost caused by displacement of the odd and even echo positions with respect to the center of the acquisition window. The echo time-shifts cause phase shifts in the spatial (frequency) domain. The Nyquist ghost is usually corrected by using a reference scan collected without the phase-encode gradients and the procedure is summarized below.

1. Collect a reference scan, R+, with phase encode gradient off
2. Reverse the even echoes
3. FT along the read dimension
4. Determine the phase, P+, of each data point
5. Collect the EPI data, E+
6. Reverse the even echoes
7. FT the EPI data along the read dimension
8. Subtract the reference phase obtained in (4)
9. FT along the phase dimension
10. Calculate the magnitude of the image for display

The above procedure, also referred to as the nonlinear phase correction method, removes most of the Nyquist ghost artifact, but often the images show a residual ghost artifact on the order of 2-5% and sometimes even as high as 25%. These residual artifacts are caused by subtle differences between the odd and even echoes. For example, residual eddy currents and the analog filter can affect the odd and even echoes differently because the even echoes are time reversed prior to data processing. Eddy currents and the analog filters influence conventional data as well, but their effect is the same for all the echoes. Interestingly, if the even and odd echoes in an EPI dataset are separated and processed, no Nyquist ghost artifacts are observed.

It has been proposed that the Nyquist artifact can be reduced in EPI images by collecting two phase-encoded reference scans with a) normal read gradients and b) with the read gradient polarity reversed (1,2). The artifact reduction with respect to a non-phase encoded reference scan reported in Reference 1 is given below.

The ghost-to-signal levels (%) reported in the literature (2), from nine human subjects, are given below. (A) and (B) refer to the non-phase encoded and phase-encoded reference scan methods respectively.

A	8.1	5.5	10.6	5.5	5.1	2.6	5.6	3.6	5.1
B	2.9	1.6	1.7	4.5	1.5	1.3	2.1	1.7	3.4

Based on the principle of using both normal and inverted readout gradients (1,2), a new phase correction method was implemented for EPI. The current implementation on the Varian system appears to be simpler than the methods described previously in the literature and requires a minimum of three reference scans:

a) Non-phase encoded reference scan, R+
b) Non-phase encoded reference scan with the read gradient polarity reversed, R-
c) Phase-encoded reference scan with the read gradient polarity reversed, E-

The procedure for processing is as follows:

1. Reverse the even echoes in the R+ dataset
2. FT along the read dimension
3. Generate the nonlinear phase map, P+
4. Reverse the odd echoes in the R- dataset
5. FT along the read dimension
6. Generate the nonlinear phase map, P-
7. Phase correct the phase-encoded reference data, E-, using P- to give E*-
8. Reverse the even echoes in the EPI dataset, E+
9. FT along the read dimension
10. Phase correct the EPI data using P+, to give E*+
11. Apply the odd/even echo correction by complex addition of E*- and E*+
12. Apply the FT along the phase encode direction
13. Display the magnitude image

The nonlinear phase correction for EPI is currently used in VnmrJ software using a single reference scan. The new artifact correction method, referred to as triple-reference scan method, is implemented in the VnmrJ2.1C software.

Results

The EPI ghost reduction method was tested using phantom data measured on the 4.7T and 9.4T Varian MRI Systems (Figures 2 and 3, respectively) at Varian, Inc., Palo Alto, CA. The standard, nonlinear phase correction gave about 3-5% residual ghosting. After the new phase correction scheme, the ghosting level was down to about 0.3-0.75%, and in some cases down to the noise level.

Experimental

Load and set up the EPI protocol as described in the Imaging User manual. Select the triple-reference scan option in the Acquire page. The reference scans are indicated by the values of the parameter image -1 refers to the image dataset and 0 refers to the standard non-phase encoded reference scan. Similarly, -2 and -1 refer to the R- and E- datasets, respectively. In a long experiment, the three reference scans may be distributed in the array specifying the image parameter to compensate for long term variability such as temperature and associated field drift.

a) Load and set up the EPI sequence as usual (use EPI.C in VnmrJ2.1)

b) Select the triple-reference scan option. This sets image = 0, -2, -1, 1, 1, 1, 1, 1, 1, 1

c) Click on Start Scan to initiate acquisition. The data will be collected, processed and saved.

d) To display them in either the Plan or Review View Port, double-click on epi icon in Study Q.

Discussion and Summary

The phase correction method using three reference scans appears to reduce the Nyquist ghost levels significantly. Our current ATP specification for EPI ghosts is <5%. Four datasets on two systems (4.7T and 9.4T) showed that the ghosting levels were reduced to about 0.7% or less. In the limited tests conducted so far, the results appear to be significantly improved over those reported in the literature (1,2). The improvement may be due to the inclusion of two non-phase encoded reference scans. The

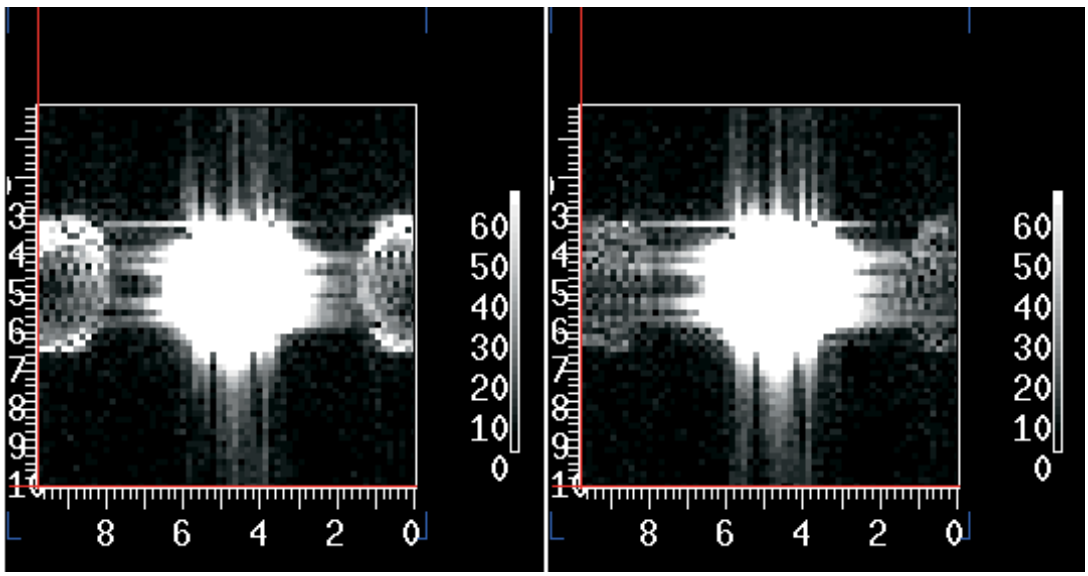

Figure 2 EPI images taken at 4.7T using the 12cm 40G/cm Magnex gradient. The image on the left was processed using the standard nonlinear phase correction using a single reference scan. The one on the right was processed using three reference scans. The largest ghost level was reduced from 3.5% to 0.64%. All the images from nine EPI datasets showed similar results. The same vertical scaling was used for both displays. The vertical scaling was adjusted to emphasize the noise region.

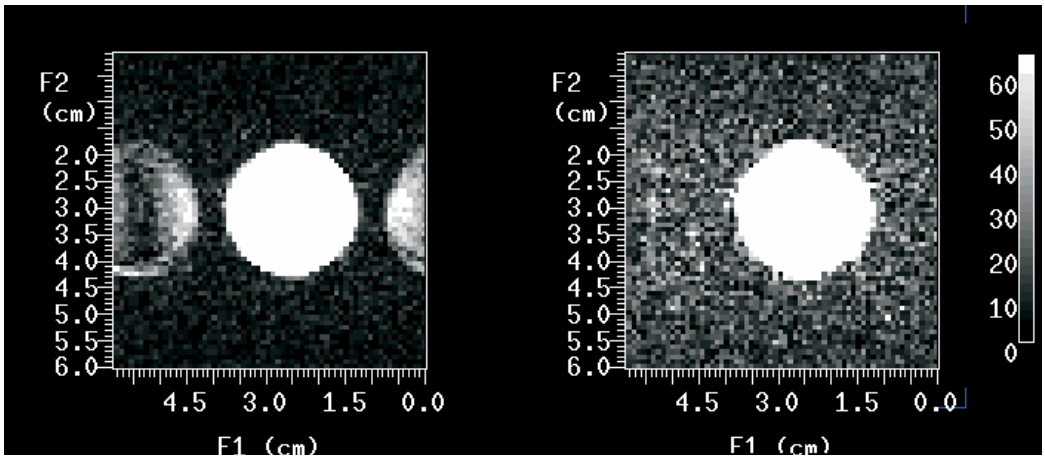

Figure 3 EPI image taken at 9.4T. The image on the left was processed using the standard nonlinear phase correction whereas the image on the right was processed using three reference scans. The ghost level for the one on the left was 4.5%. The best result from an array of five EPI datasets is shown here. The other datasets, when processed, showed a ghost level of 0.5% or less.

additional reference scans should not significantly increase the total scan time in typical fMRI studies where a few steady state scans are run prior to the actual scan.

In the study done at 9.4T, the echoes were perfectly aligned after the EPI pre-scan setup procedure. Under these conditions the images processed with only the E- reference scan worked as well as those using all three reference scans. In general, if the echoes show a "tilt" or "shift," three reference scans shall be used.

If there is motion or significant change in image intensity or phase after the reference scans are taken, the artifact correction method will fail. By taking reference scans periodically during a long EPI run, time-dependent variations in the image can be minimized.

References

1. X. Hu and T. H. Le, Magn. Reson. Med. 36:166-171 (1996)
2. N. Chen and A. M. Wywicz, Magn. Reson. Med. 51:1247-1253 (2004)

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